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SATELLITE BROADCASTING: bandwidth requirements for f.m. television signals

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SATELLITE BROADCASTING: BANDWIDTH REQUIREMENTS FOR FM TELEVISION SIGNALS

N.H.C. Gilchrist, B.Sc., C.Eng., M.I.E.E.

Summary

A practical investigation has been conducted in order to determine the r.f. bandwidth required to transmit, with an acceptably low level of distortion, 625-line Standard I PAL colour television signals by frequency-modulation with various values of modulation index. The work described includes measurements made on a proposed sub-carrier sound system, and an examination of the performance of a f.m. television system near the noise threshold.

Values for bandwidth and deviation are recommended for f.m. television broadcasting (including the sound signal) from satellites.

Issued under the authority of

P. Rainger

Head of Research Department

Research Department, Engineering Division,
BRITISH BROADCASTING CORPORATION

(EL-80)

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1. Introduction

A television service which is broadcast from a satellite is subject to a number of technical restrictions. The principal restriction appears to be that the output power of the transmitter is limited, as the resources of an economic satellite are insufficient to support a heavy electrical load. Limitations on the power which can be radiated make it necessary to use a wide-band transmission system in order to overcome noise problems at the receiver; this means that f.m., pulse code modulation (p.c.m.), or some similar system of modulation must be used.

When a satellite television service is being planned, it is necessary to know the bandwidth which will be required for each television channel so that the maximum use may be made of the frequency band available. This report describes some of the work which has been done at the BBC Research Department to assess the optimum ratio of channel bandwidth to carrier deviation for a f.m. television broadcasting system. This experimental work complements the theoretical studies that have been made on this problem.[1]

2. Experimental arrangement

The experimental work was conducted using the arrangement shown in Fig. 1. The f.m. modulator and demodulator used were commercial units operating with a carrier rest frequency of 70 MHz, which is an intermediate frequency commonly used in s.h.f. link equipment. The positive excursion of the vision signal causes a reduction in frequency of the carrier, and the negative excursion gives an increase in frequency. In order to achieve a satisfactory limiting characteristic in the demodulator unit, it was found necessary to include amplifiers at 70 MHz providing a gain of about 30 dB.

Characteristics of the bandpass filters used to simulate the i.f. filter in the receiver are shown in Figs. 2 – 7. The filters are 6-section, of the type developed by Cohn, using inductors formed by etching a spiral pattern in the surface of a printed circuit board, and have a well defined passband with fairly steep skirts. The group-delay characteristics are not particularly satisfactory, showing quite a large variation at the edges of the passband (typically 100 ns). It is unlikely that elaborate group-delay corrected filters would be produced for satellite-broadcast receivers, so the use of a relatively simple filter in the laboratory simulation is justified.

Two still colour slides were used in a flying-spot scanner to produce colour television pictures. They were 'Boy with Toys' and 'Girl Wearing a Headscarf', and they are shown (in monochrome) in Figs. 8(*a*) and 8(*b*) respectively.

3. Tests with a vision signal only

The initial experimental work concentrated on a study

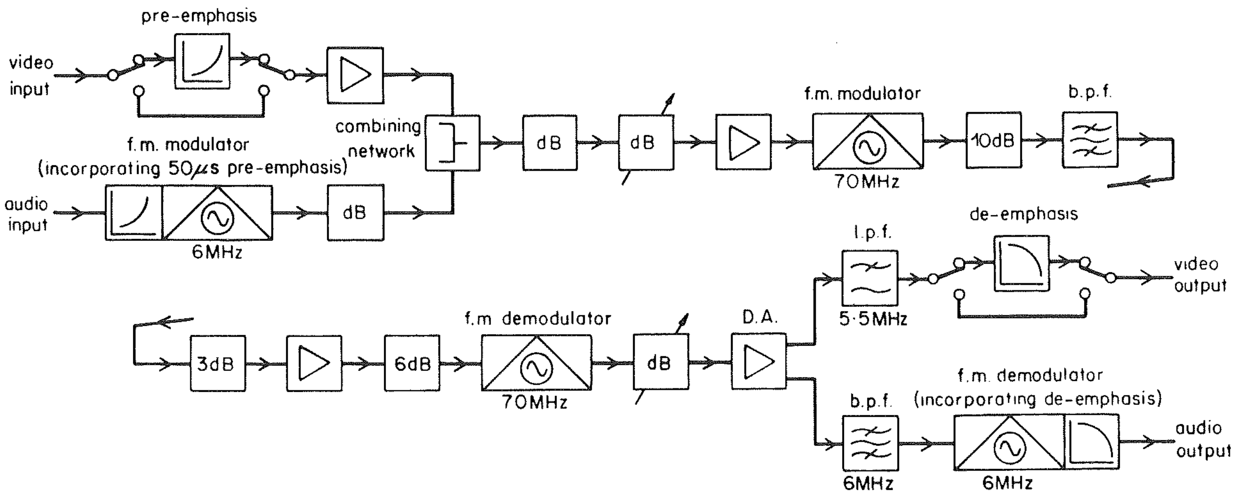

Fig. 1 - Experimental arrangement

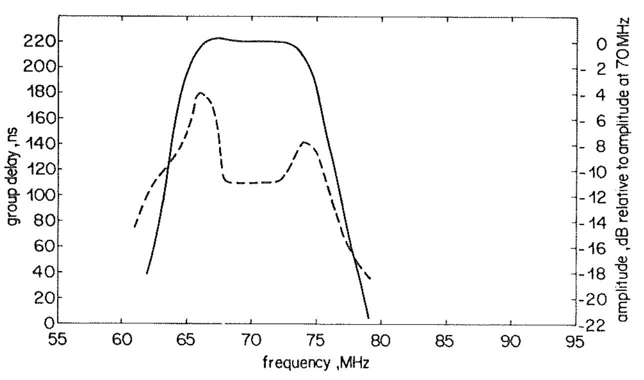

Fig. 2 - Amplitude-frequency response and group delay-frequency response of 10 MHz bandwidth Cohn filter

——— Amplitude-frequency response

– – – – – – Group delay-frequency response

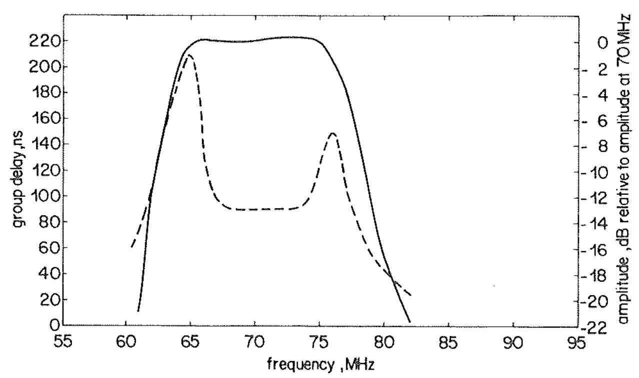

Fig. 3 - Amplitude-frequency response and group delay-frequency response of 13 MHz bandwidth Cohn filter

——— Amplitude-frequency response

– – – – – – Group delay-frequency response

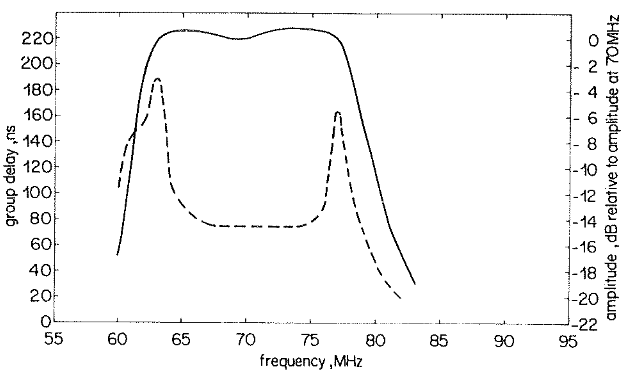

Fig. 4 - Amplitude-frequency response and group delay-frequency response of 15 MHz bandwidth Cohn filter

——— Amplitude-frequency response

– – – – – – Group delay-frequency response

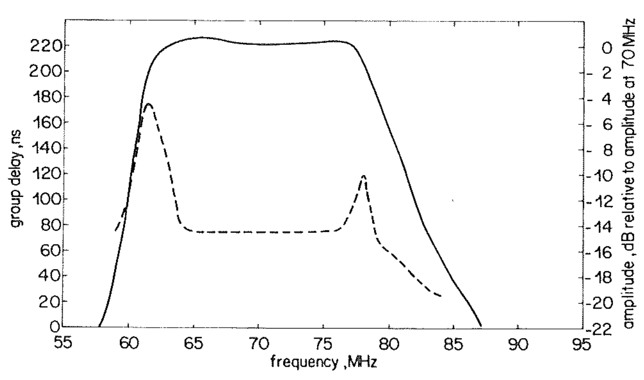

Fig. 5 - Amplitude-frequency response and group delay-frequency response of 17 MHz bandwidth Cohn filter

——— Amplitude-frequency response

– – – – – – Group delay-frequency response

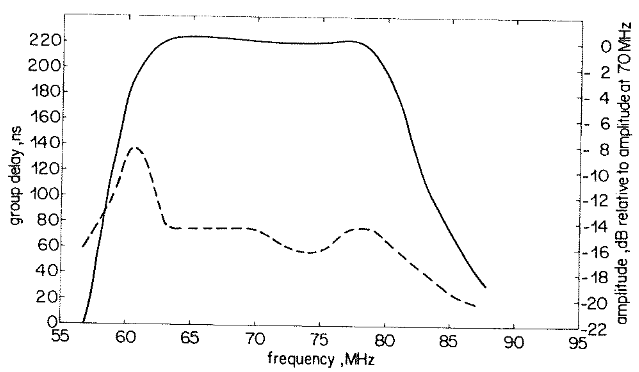

Fig. 6 - Amplitude-frequency response and group delay-frequency response of 19·5 MHz bandwidth Cohn filter

——— Amplitude-frequency response

– – – – – – Group delay-frequency response

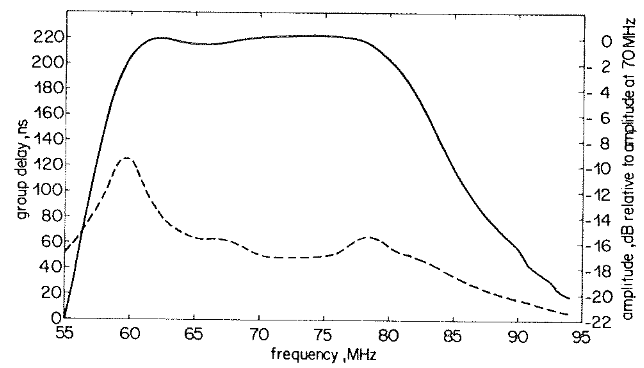

Fig. 7 - Amplitude-frequency response and group delay-frequency response of 22 MHz bandwidth Cohn filter

——— Amplitude-frequency response

– – – – – – Group delay-frequency response

(a)

(b)

Fig. 8 - Slides used for the tests
(a) Boy with toys *(b)* Girl wearing a headscarf

of the effects of limiting the bandwidth of a 70 MHz f.m. vision signal without an accompanying sound signal. A broadcast television programme would need at least one accompanying sound signal but it was thought that an initial series of tests to establish the relationship between deviation, bandwidth and picture quality without the added complication of a sound channel would be helpful.

Several test waveforms were passed through the system and checked for distortion. Restricting the r.f. bandwidth produced crosstalk between luminance and chrominance information and a fall-off in response to the higher video frequencies.

Preliminary measurements were made of the chrominance/luminance gain and delay inequality, the differential gain and phase of the colour subcarrier and the pulse and bar response, to determine which form of test was the most sensitive indication of picture degradation. It was found that the differential gain and phase measurements satisfied this requirement and were therefore used as the basis of the objective tests.

The test waveforms used were the 'staircase', and two CCIR modified waveforms (all with colour subcarrier). The staircase waveform has five steps, with colour subcarrier on each step and occurs on every line; one CCIR waveform has one line of steps plus three of black level, and the other has one line of steps with three of peak white level. Results of tests conducted with and without pre-emphasis showed that the use of pre-emphasis greatly reduced the differential gain and phase distortion. The video signal was pre-emphasised before modulation and de-emphasised after demodulation in accordance with the CCIR Recommendation,[2] and the deviations quoted are those for a 1 volt peak-to-peak sinusoidal signal at 1·512 MHz (the pre-emphasis network has unity gain at this frequency). The input video signal, before pre-emphasis, had an amplitude of 1 volt between peak white level and sync. tip.

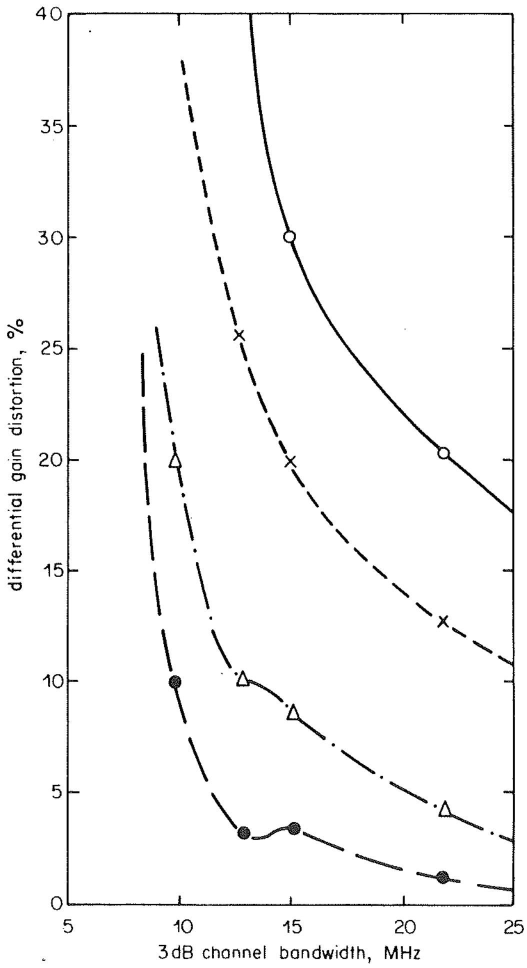

Fig. 9 - Differential gain distortion as a function of bandwidth

O——O 14·26)
x- - -x 10·04) Peak-to-peak deviation, MHz
Δ—·—Δ 5·7)
●— —● 2·1)

Fig. 9 shows graphs of differential gain distortion of the colour subcarrier as a function of bandwidth for a number of deviations, and the corresponding graphs for differential phase distortion are shown in Fig. 10. The graphs were plotted from results obtained for whichever of the three test waveforms gave the highest distortion.

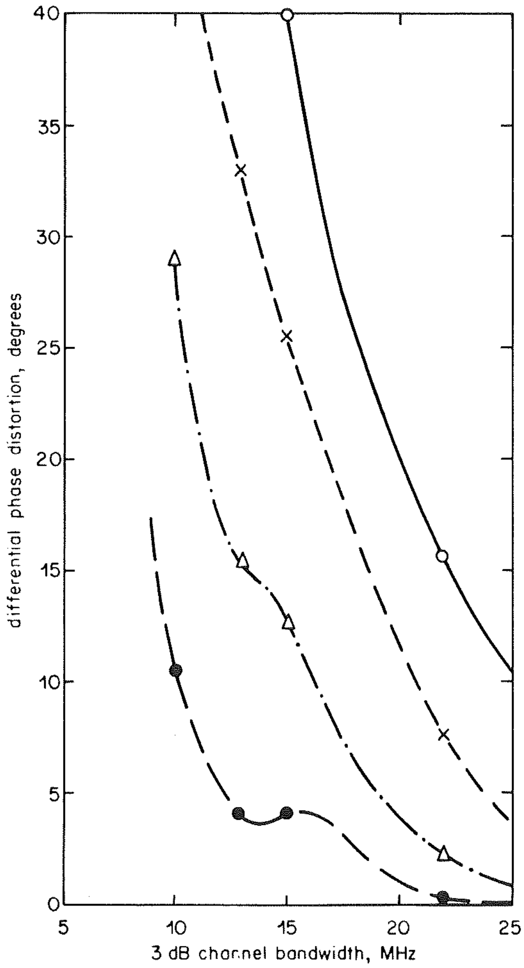

Fig. 10 - Differential phase distortion as a function of bandwidth

O——O 14·26)
X- - -X 10·04) Peak-to-peak deviation, MHz
Δ—·—Δ 5·7)
●— —● 2·1)

A panel of viewers (nine technical staff) were asked to assess the quality of a colour television picture (Boy with Toys) which had been sent through the system using various combinations of bandwidth and deviation. They were shown a typically 'bad' picture in which there was severe de-saturation of coloured highlights as well as disturbance to certain luminance transitions, exemplifying the type of impairment produced by the transmission faults under investigation; they were then asked to grade pictures with various degrees of disturbance according to a 6-point quality scale.* The results are shown in the graphs of Fig.

* The 6-point quality scale used was that given in CCIR Report 405-1 (New Delhi, 1970), Note 6, and is as follows:

1. Excellent	3. Fairly Good	5. Poor
2. Good	4. Rather Poor	6. Very Poor

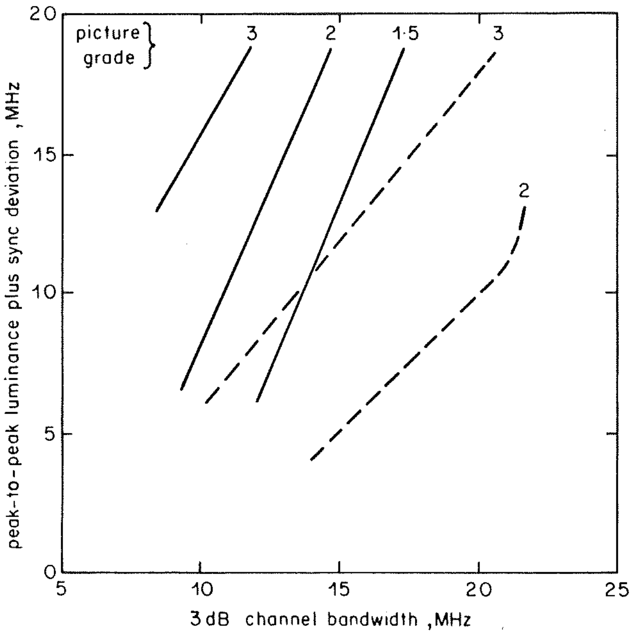

Fig. 11 - The relationship between deviation and r.f. bandwidth for a f.m. television signal (without sound)

———— Results obtained with pre-emphasis
- - - - - - Results obtained without pre-emphasis

11. It was decided that all subsequent tests should include video pre-emphasis, as this is so effective in reducing distortion.

4. Tests with vision and sound signals

A sound signal was added to the vision signal, before modulation, in the form of a 6 MHz frequency-modulated subcarrier. The subcarrier was added to the 1 V television signal (i.e. 1 V peak white to sync tip measured before pre-emphasis) after the video pre-emphasis network. Most of the tests were conducted with a maximum subcarrier deviation of ±50 kHz and a subcarrier amplitude of 150 mV peak-to-peak, giving the subcarrier 13% of the total main-carrier deviation.* Unless otherwise stated, these parameters apply to any vision plus sound signal for which results are presented in this report.

The sound signal was subjected to the standard 50 μs pre- and de-emphasis.

4.1. Performance of the vision channel

The panel of viewers judged the quality of a number

* This is not strictly true, as the vision signal both before and after pre-emphasis can exceed 1 V peak-peak when highly saturated colours occur with high luminance levels in the picture. Throughout this report, the total deviation of the main carrier is specified in terms of the peak-to-peak deviation produced by a television signal excursion of IV after pre-emphasis, plus the peak-to-peak deviation produced by the 6 MHz subcarrier. The true value of the peak-to-peak deviation produced by the video can be 25% greater than that for a 1 V television signal, with pictures containing areas of highly saturated colour.

of television pictures transmitted through the system with an accompanying sound signal on a 6 MHz subcarrier. The sound modulation was a 400 Hz tone deviating the subcarrier to the full ±50 kHz for most of the examples to be judged, but examples with programme modulation and no modulation were included. No significant difference in the results was found between the examples with different types of sound modulation or no modulation at all.

The two colour slides shown in Fig. 8 were alternated with 100% colour bars in the viewing tests. Colour bars are not normally included in subjective testing, but were used on this occasion as a convenient source of picture with large areas of highly saturated colour, bearing in mind that programme material can often consist of captions displayed against highly saturated coloured backgrounds. Both slides gave similar results, but the colour bars required a considerably greater bandwidth in order to give a satisfactory picture.

The relationship obtained between channel bandwidth and deviation is shown in the graphs of Fig. 12.

In the course of these tests it became apparent that, when a sound subcarrier is added to the vision signal, the predominant impairment of the picture produced by r.f. bandwidth restriction takes the form of a 1·57 MHz sound/chrominance beat pattern.

For a 'good' (grade 2) assessment of a picture containing large areas of saturated colour, a signal with a total deviation of 6 MHz requires a 15 MHz r.f. bandwidth and one deviated 12 MHz requires 21 MHz bandwidth; a grade 1½ picture (viewers equally divided between 'good' and 'excellent') requires bandwidths of 18 MHz and 23 MHz respectively at these deviations.

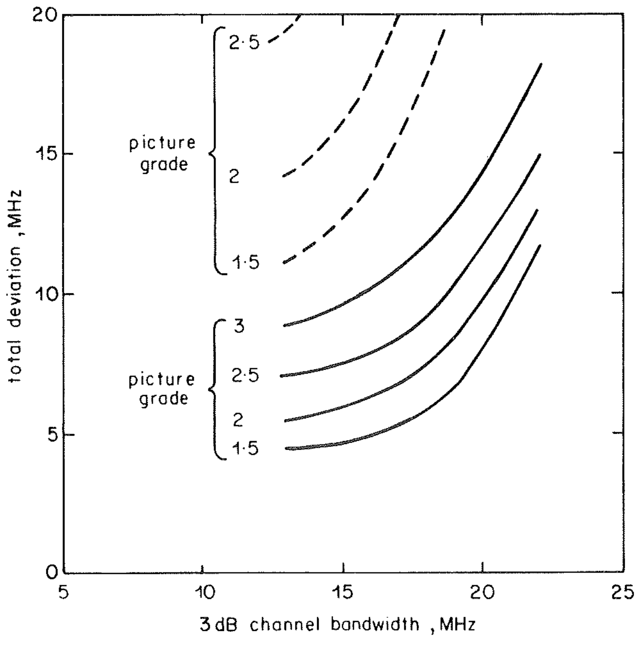

Fig. 12 - The relationship between deviation and r.f. bandwidth for a f.m. television signal (with sound)

- - - - - Results for tests using slides
———— Results for tests using colour bars

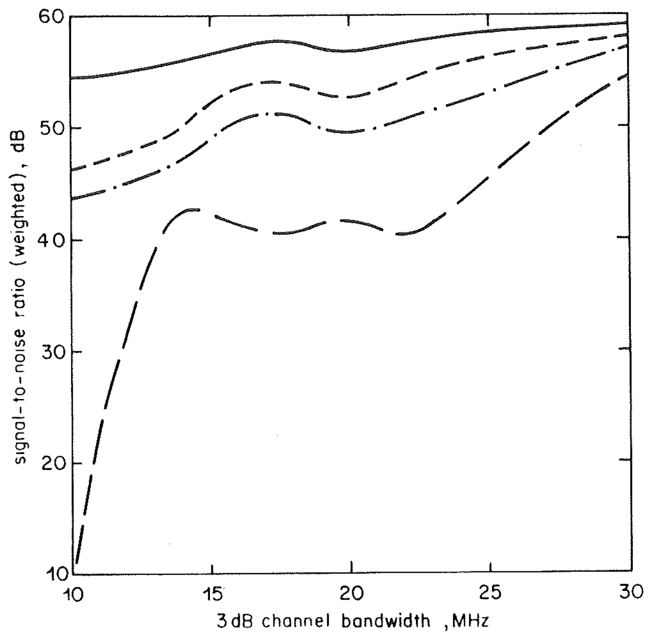

Fig. 13 - Sound signal-to-noise ratio as a function of bandwidth

————	2·4)	Total deviation, MHz
– – –	6·6)	
—·—	9·2)	
— —	16·4)	

4.2. Performance of the sound channel

Sound signal-to-noise ratios were measured for a number of deviations and bandwidths with a Niese (O.I.R.T.) meter, modified to BBC requirements,[3] using the CCIR[4] weighting network. This combination of measuring equipment has been found to give the best agreement with subjective assessments of the impairment produced by different types of noise and disturbance in sound circuits, and was chosen for a series of objective tests as a suitable alternative to the relatively time-consuming subjective tests. Fig. 13 shows the results of the sound signal-to-noise tests; reference level for these tests was full modulation at 1 kHz. No allowance was made for sound pre-emphasis at 100% modulation, because it is anticipated that a frequency-dependent limiter will be used to control sound modulation.

The picture information consisted of 100% colour bars, as this was found to give a higher noise level in the sound channel than any of the slides available. A listening test revealed that the noise was predominantly a 'buzz' — the result of vision-to-sound crosstalk.

Tests were also carried out with different deviations of the subcarrier by the audio tone and with different deviations of the main carrier by the subcarrier. Doubling the deviation of the subcarrier by the 1 kHz tone improved the signal-to-noise ratio by about 6 dB when vision-to-sound crosstalk was present. Increasing the amplitude of the subcarrier relative to the vision signal in the presence of vision-to-sound crosstalk produced relatively little change in the signal-to-noise ratio.

The impairment threshold,[3] which is defined as the noise level at which the noise just obtrudes upon consciousness under listening-room conditions, is reached when the signal-to-noise ratio is 60 dB (as measured with the modified Niese meter and CCIR[4] network). It seems unnecessary to aim for such a high standard for broadcast reception of the sound associated with television, and it is suggested that 50 dB to 55 dB is a suitable value for the signal-to-noise ratio. The graph of Fig. 13 shows that for this standard of performance from the sound channel and with 13% deviation allocated to the sound subcarrier, the r.f. bandwidth required is about 15 MHz for a total deviation of 6 MHz, and 24 MHz for a total deviation of 12 MHz. Reference to Section 4.1 shows that a picture graded 1½ to 2 would be obtained using these bandwidths and deviations.

5. Tests on operation of vision-plus-sound system near the noise threshold

If the carrier-to-noise power ratio at the input to the frequency demodulator is progressively reduced, a point is reached where the noise at the output of the receiver changes from gaussian to a predominantly impulsive type. The carrier-to-noise ratio at which the transition occurs is termed the noise threshold and the impulses are caused by the relatively large phase perturbations (2π radians) of the received carrier which can occur when the noise peaks in the i.f. pass-band exceed the amplitude of the carrier.

5.1. Performance of the vision channel

In order to save time, particularly in subjective tests, only two of the filters were used, and two deviations were selected for use in each bandwidth. The combinations of bandwidth and deviation tested were 22 MHz bandwidth with deviations of 13·0 MHz and 18·3 MHz, and 17 MHz bandwidth with deviations of 10·3 MHz and 6·5 MHz. Two of the wider bandwidth filters were selected because it was considered that satellite broadcasts would need relatively wide channels in order to use f.m. to the best advantage.

The video signal-to-noise ratio was measured at the output of the receiver with a video noise meter (BBC type ME1M/503) measuring r.m.s. noise level, unweighted, relative to a 0·7 volt luminance signal in the absence of modulation for a number of carrier-to-noise ratios.* The graphs of Fig. 14 show the results obtained. The noise threshold is at a carrier-to-noise ratio of about 10 dB. Below the threshold, the curves have a relatively steep slope.

The performance of the system under these conditions was then assessed subjectively. The panel of viewers judged the quality of a slide (Boy with Toys) and colour bars, presented alternately, when the system was operating

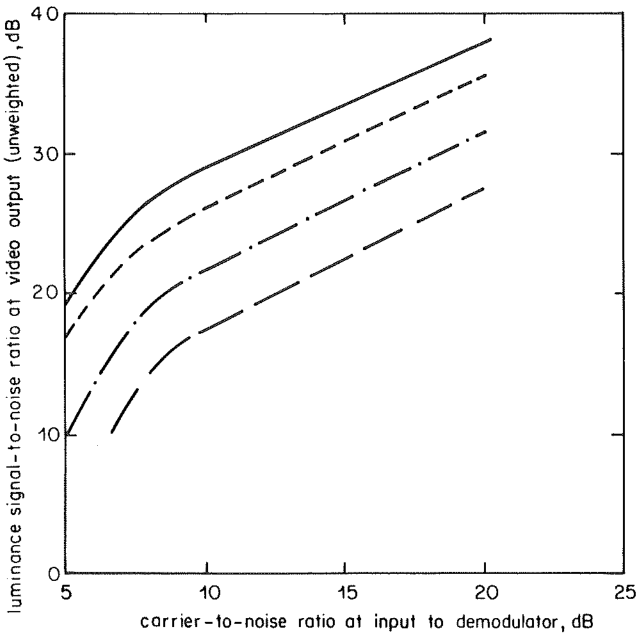

Fig. 14 - Luminance signal-to-noise ratio as a function of carrier-to-noise ratio

———	18·3	Total deviation, MHz, used with 22 MHz, bandwidth
– – –	13·0	
—·—	10·3	Total deviation, MHz, used with 17 MHz, bandwidth
— —	6·5	

near to the threshold. Figs. 15 and 16 show the results obtained with r.f. bandwidths of 17 MHz and 22 MHz respectively.

The measurements described in Section 4.1 and illustrated in Fig. 12 showed that, under relatively *noise-free* conditions, the subjectively-assessed picture quality deteriorates as the deviation/bandwidth ratio increases.

The results of Fig. 15 show the opposite tendency,

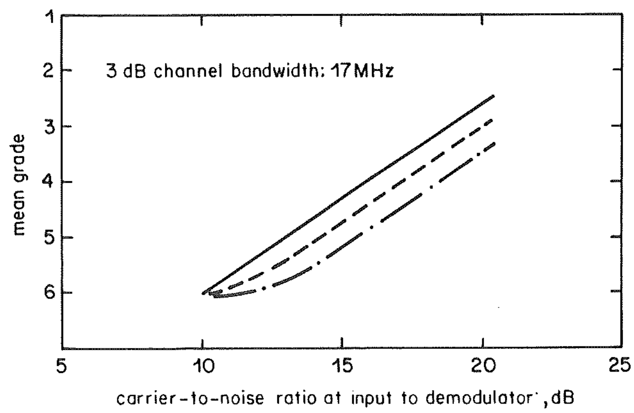

Fig. 15 - Mean grade awarded to picture as a function of carrier-to-noise ratio, 17 MHz bandwidth

	Total deviation, MHz	Vision Signal
———	10·3	Slide and colour bars
– – –	6·5	Colour bars
—·—	6·5	Slide

* The noise was produced by a diode noise generator and amplifier and injected immediately before the 70 MHz bandpass filter. By this means, the carrier could be maintained at a constant level throughout the tests, thus ensuring that the receiver limiter was fully operative.

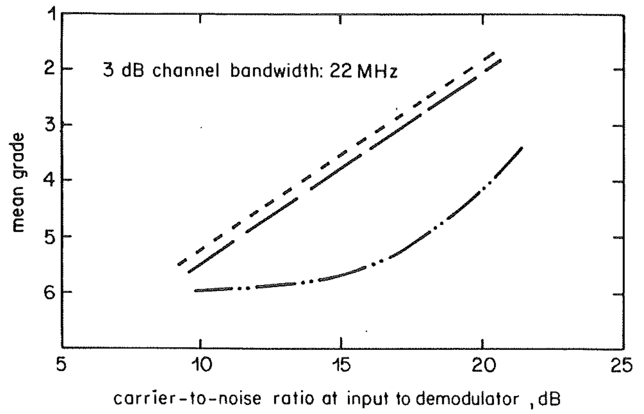

Fig. 16 - Mean grade awarded to picture as a function of carrier-to-noise ratio, 22 MHz bandwidth

	Total deviation, MHz	Vision Signal
----	13·0	Slide and colour bars
——	18·3	Slide
—··—	18·3	Colour bars

with the quality assessment improving with increasing ratio of deviation to bandwidth. This indicates that, over the range of conditions tested, noise was the dominant impairment. The results obtained with the 22 MHz bandwidth (Fig. 16) show the picture assessment becoming worse with increasing deviation, as was found in the earlier measurements made in the absence of noise.

It was noticed in the course of the tests with 22 MHz bandwidth that one visible effect of increasing deviation with a very noisy signal was a coarsening of the noise structure in the picture. This apparent increase of the low-frequency noise components, noticeable in areas of saturated colour, is thought to be caused by intermodulation between noise and the colour subcarrier.

In order to investigate further the effects of noise on the optimum deviation/bandwidth ratio another series of subjective tests was conducted, with carrier-to-noise ratios of 16 dB in 17 MHz bandwidth and 14 dB in 22 MHz bandwidth, using the 'Boy with Toys' slide alternated with colour bars, over a range of deviations.

The mean grading assessments awarded to the slide and colour bar pictures are shown separately in Figs. 17 and 18. Although the results for the slide improve continuously with increasing deviation throughout the range investigated, those for colour bars show a fairly well defined optimum at a deviation/bandwidth ratio of about 0·6. Even under noisy conditions, therefore, in order to ensure that pictures containing large areas of saturated colour are not unduly impaired, these results imply that the total deviation should not exceed about 70% of the r.f. bandwidth.

A number of 'good' and 'excellent' television pictures were included in the tests of Figs. 17 and 18 in order to prevent the viewers from becoming conditioned to accept indifferent picture quality. These latter examples were necessarily obtained by operating well above the noise

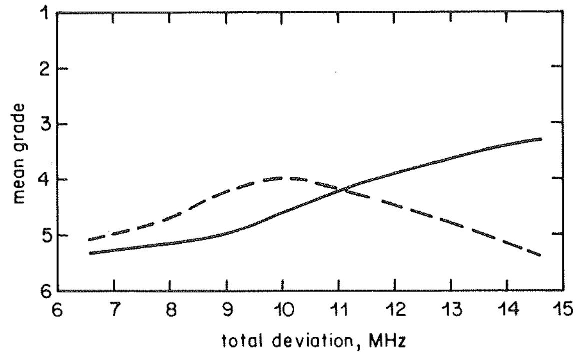

Fig. 17 - Mean picture grade as a function of deviation, 16 dB carrier-to-noise ratio, 17 MHz bandwidth

——— Results for tests using slide
------ Results for tests using colour bars

threshold, and the results obtained for them were ignored, as their purpose was purely psychological.

5.2. Performance of the sound channel

The signal-to-noise ratio of the sound channel was measured using the modified Niese meter and CCIR[4] network, as before, for a number of carrier-to-noise ratios. Colour bars were used for the video signal, as these had been found to give the greatest degree of crosstalk into the sound channel in the previous measurements. Tests were conducted also with only black level and syncs on the vision channel, for comparison with the results for colour bars.

The results obtained for a 17 MHz r.f. bandwidth are shown in Fig. 19 and those for a 22 MHz bandwidth in Fig. 20. Halving the deviation of the 6 MHz subcarrier by the audio modulation reduces the signal-to-noise ratio measured in the sound channel by 6 dB. Doubling the amplitude of the subcarrier before it is added to the vision signal (and reducing the amplitude of the vision signal by 1 dB to keep the total deviation approximately the same)

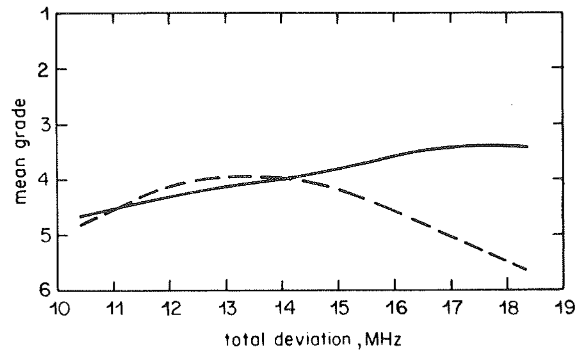

Fig. 18 - Mean picture grade as a function of deviation, 14 dB carrier-to-noise ratio, 22 MHz bandwidth

——— Results for tests using slide
------ Results for tests using colour bars

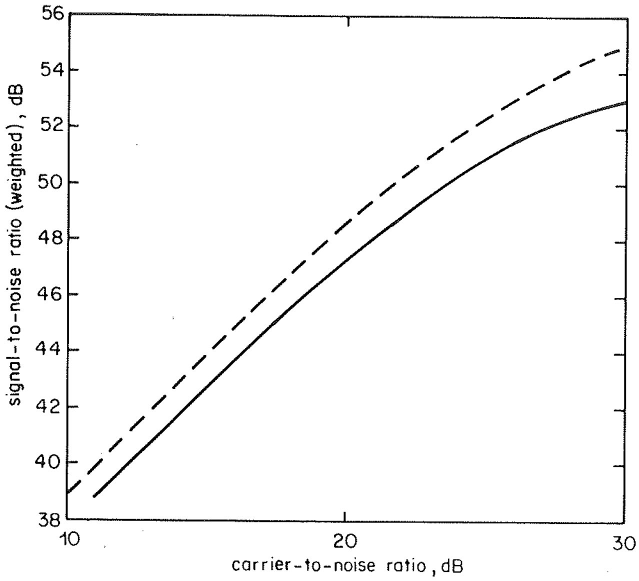

Fig. 19 - Sound signal-to-noise ratio as a function of carrier-to-noise ratio. Total deviation 10·3 MHz, bandwidth 17 MHz

——— Colour bars) Vision signal
- - - - - - Black level and syncs)

increases the signal-to-noise ratio by rather less than 6 dB; typically 2 to 3 dB.

6. Discussion and conclusions

The parameters to be adopted for a satellite broadcasting system are determined ultimately by the minimum carrier-to-noise ratio which will exist at the input to the demodulator of a receiver. Measurements of the video

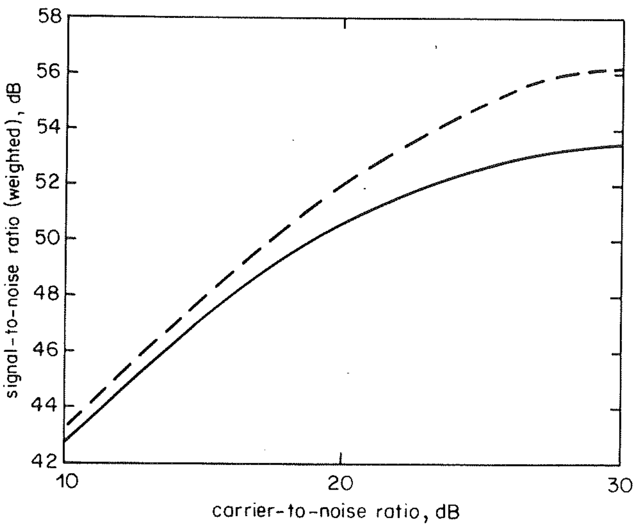

Fig. 20 - Sound signal-to-noise ratio as a function of carrier-to-noise ratio. Total deviation, 14·6 MHz, bandwidth 22 MHz

——— Colour bars) Vision signal
- - - - - - Black level and syncs)

signal-to-noise ratio after demodulation have shown that the performance of the system deteriorates rapidly below the noise threshold occurring at about 10 dB carrier-to-noise ratio, but satisfactory results can be obtained with a f.m. system operating just above the noise threshold. Sub-group K3 of the European Broadcasting Union have suggested that sufficient transmitter power should be provided to give a minimum carrier-to-noise ratio of 14 dB at the demodulator for 99% of the time in the worst month of the year; this would achieve a margin of about 4 dB above the threshold. It is anticipated that the carrier-to-noise ratio would only fall to 10 dB for about 0·1% of the time, when propagation conditions are extremely unfavourable.

A series of tests investigating the relation between bandwidth and distortion of a f.m. signal in the absence of noise has shown that, in particular, a system with 13 MHz total deviation (including both vision signal and a sound subcarrier) would require about 22 MHz r.f. bandwidth to ensure a picture quality not worse than grade 2 using the CCIR 6-point quality scale. Under noisy conditions, for a system operating in the same bandwidth, there is an optimum deviation of about 14 MHz; at lower deviations noise is the predominant impairment, and at higher deviations the effects of non-linear distortion predominate. It is suggested, therefore, that the r.f. bandwidth provided for the complete f.m. television signal should be about 1·6 times the total deviation.

Taking into account the picture quality that must be achieved at 14 dB carrier-to-noise ratio it is considered, on the basis of the results presented in this report, that a satellite f.m. television broadcasting system on 625 line, Standard I, should employ a total deviation of about 18 MHz, comprising 14 MHz peak-to-peak deviation for a 1 volt video signal after pre-emphasis in accordance with the CCIR Recommendation[2] plus a deviation of ±2 MHz peak by the 6 MHz sound subcarrier (corresponding to a 280 mV peak-to-peak sound subcarrier added to the 1 volt video signal after pre-emphasis). The audio-frequency programme would be pre-emphasised with the standard European 50 μs time constant and would deviate the sound subcarrier to a maximum of ±50 kHz, enabling the receiver to use conventional intercarrier sound circuits. By a small extrapolation of the measured results it is estimated that a system with these parameters would need a r.f. bandwidth of 28 MHz, and give a picture subjectively graded not worse than 3 (corresponding to a measured video signal-to-unweighted-noise ratio of 33 dB) with a carrier-to-noise ratio of 14 dB. The sound signal-to-noise ratio would be at least 50 dB (weighted).

The preliminary tests conducted on a vision-only system (described in Section 3) have shown that a greatly reduced bandwidth can be used if no sound subcarrier is transmitted. For example, if we take a signal with the recommended peak-to-peak deviation of 14 MHz for the vision signal with no sound added, an overall quality grade 1½ picture can be obtained with a bandwidth of only 16 MHz. Thus it would appear that an alternative method of sound signal distribution (e.g. a separate sound carrier) would enable considerable economies in bandwidth to be effected, but the non-linearity resulting from the saving of

bandwidth raises the levels of differential gain and differential phase distortion to 28% and 39 degrees respectively. These distortions which show as de-saturation of coloured highlights in the picture when the bandwidth is restricted would affect all viewers, and be apparent under all propagation conditions. It may therefore be unwise to allow the process of transmission from the satellite and reception by the domestic receiver to contribute more than one third of the total permissible distortion. The optimum distribution of tolerances will depend on the performance of the programme circuits feeding the satellite. It has been assumed, in this report, that the level of distortion in the signal fed to the satellite will be the same as that in the programme feed to a terrestrial rebroadcast transmitter.[5] If an overall picture grade of 1½ is acceptable, sufficient bandwidth must then be provided to keep the differential gain and differential phase distortion down to about 11% and 11 degrees for the transmission from the satellite to the receiver. The overall performance of the whole broadcast chain from the studio centre to the receiver would then be capable of giving a grade 1½ picture.

For a bandpass filter that is not group-delay corrected this level of performance would require a bandwidth of 27 MHz for the vision-only signal with 14 MHz peak-to-peak deviation, and so it appears that under these assumptions a subcarrier sound channel does not appreciably increase the bandwidth requirements of the system.

7. References

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